

Disentangling the Dynamical Mechanisms for Cluster Galaxy Evolution

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ABSTRACT. The determination of the dynamical causes of the morphological Butcher-Oemler (BO) effect, or the rapid transformation of a large population of late-type galaxies to earlier Hubble types in the rich cluster environment between intermediate redshifts and the local universe, has been an important unsolved problem that is central to our understanding of the general problems of galaxy formation and evolution. In this article, we survey the existing proposed mechanisms for cluster galaxy transformation, and discuss their relevance and limitations to the explanation of the morphological BO effect. A new infrared diagnostic approach is devised to disentangle the relative importance of several major physical mechanisms to account for the BO effect, and an example of the first application of this procedure to a single rich intermediate redshift galaxy cluster is given to demonstrate the viability of this approach. The preliminary result of this analysis favors the interaction-enhanced secular evolution process as the major cause of the cluster galaxy morphological transformation. This conclusion is also supported by a wide range of other published results that are assembled here to highlight their implications on a coherent physical origin for the morphological BO effect.

1. INTRODUCTION

Central to the study of the cosmic evolution of galaxies is the identification of the dominant dynamical mechanism responsible for the rapid transformation, between intermediate redshifts and the local universe, of cluster galaxies from a population characterized by a significant fraction of late-type spirals to one dominated by S0s and ellipticals: the so-called morphological Butcher-Oemler (BO) effect (Butcher & Oemler 1978a, 1978b; Dressler et al. 1997).

At the heart of the BO effect is the spiral to early-type transformation (Dressler et al. 1997; Ellis 1998). This transformation not only involves the extinguishment of the star-formation activity, but also the gradual increase of bulge-to-disk ratio (Franx 2004; Treu 2004 and references therein). Furthermore, whichever physical mechanism(s) produced the BO effect, in addition to producing the observed number density evolution of cluster galaxies, must simultaneously be able to preserve the relatively tight color-magnitude relation observed throughout the redshift range $z = 0-1$ (van Dokkum & Franx 2001). The relevant process for galaxy transformation must also preserve the outer disks and spiral structures observed for many of these galaxies during the quenching of star formation and the morphological transformation (Couch et al. 1998; Poggianti et al. 1999; Goto et al. 2003b).

Several candidate mechanisms have been proposed to account for the morphological BO effect. These include major and minor mergers (Icke 1985; Kauffmann 1995), galaxy harassment through tidal shocks (Moore et al. 1996, 1998, 1999), galaxy infall onto the forming cluster and the resulting stripping

of either the disk or halo gas (with the latter having the name of “starvation”) due to the ram pressure of the intracluster medium (Gunn & Gott 1972; Larson et al. 1980), as well as a newly discovered secular dynamical process mediated by the large-amplitude density-wave patterns excited during the tidal interaction of galaxies in clusters (Zhang 1996, 1998, 1999; Zhang & Buta 2007a, 2007b).

The dominant mechanism responsible for producing the BO effect is still uncertain. Most of the previously proposed mechanisms run into contradictions with one or another of the observed characteristics of cluster galaxies upon careful analyses. Due to the high-speed nature of galaxy-galaxy encounters within clusters, which prevents the encountering galaxies from “sticking” to one another, major mergers are not believed to have a significant probability in clusters (Dressler et al. 1997), though an exception to this conclusion has been observed for one high- z cluster (van Dokkum et al. 1998). Moreover, there does not seem to be a large reservoir of dwarf spheroidal satellites in these clusters (Trentham 1997) to cause the simultaneous morphological transformation of the large number of BO galaxies by minor mergers. The tightness of the color-magnitude relation of cluster early-type galaxies (Franx 2004 and references therein) and the well-preserved disks throughout the BO evolution process (Moran et al. 2007a and references therein) also argue against a significant role played by mergers.

Ram-pressure stripping of the interstellar medium for infalling cluster galaxies (Gunn & Gott 1972) by itself appears not to be sufficient to account for the observed level of cluster galaxy

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transformation. Stripping of gas generally does not lead to a significant change in the bulge-to-disk (B/D) ratio, though Larson et al. (1980) had envisioned the reduction of disk size due to gas stripping as one way of increasing the B/D. However, recent observations and analysis by Moran et al. (2007b) showed that cluster spiral galaxies have systematically higher central density than their field counterparts, an effect which is difficult to produce if the outer-disk stripping is the major cause of the cluster BO effect.

There is also the issue of timescale with any stripping/starvation mechanism which relies on the infall of galaxies from the field region into the centers of clusters: If an infalling galaxy starts its journey from the field at 5 Mpc distance to the cluster center and has an average velocity of 500 km/sec,¹ it takes the galaxy 4×10^9 years to reach the central region. This is a significant fraction of the Hubble time, and comparable to the cluster formation or evolution timescale. So the late-type galaxies observed in the central regions of clusters as found by Dressler et al. (1997) are likely to be primordial instead of new in-fallers from the field region. The existence of the morphology-density relation over several orders-of-magnitude variation of local surface density (Dressler 1980; Dressler et al. 1997; Goto, Yamauchi et al. 2003), from the densest region of cluster center all the way to the group environment in the field, also supports the segregation of the varying-density regions of a cluster during cluster-galaxy morphological transformation and argues against significant mixing of field populations into the central regions of clusters. Fujita (2004) proposed the idea that galaxies could be “preprocessed” in groups and intermediate density regions, which then become mixed with the cluster in somewhat less time than the field-to-cluster-core infall time. However, adding a preprocessed piece of material onto the outskirts of the cluster does not have the same effect as mixing thoroughly the material of this newly added piece into the entire cluster region including the central core. This could have allowed the preservation of the relative identities of the different cluster regions as the cluster grows and matures, as well as the maintenance of the observed morphology-density relation.

The galaxy harassment mechanism (Moore et al. 1996, 1998, 1999) has gained some popularity in recent years. When first proposed, harassment was meant as a process whereby the gravitational tidal shock from a large cluster galaxy tears away the outer disk of a small late-type neighboring galaxy, thus transforming the small galaxy into an early-type dwarf spheroidal galaxy. Numerical simulations by Moore et al. (1998) showed that the harassment process generates remnants that are predominantly prolate in shape, as opposed to the oblate

shape that an S0 galaxy (which is the typical end product of BO transformation) usually has. The follow-on exploration of the harassment mechanism by Gnedin (1999, 2003) showed that this mechanism is rather inadequate in transforming the morphology of large disk galaxies: Even though a moderate puffing-up of the entire disk was observed, there is not a significant increase in the bulge-to-disk ratio, which is a required element for the spiral-to-S0 transformation. The simulations conducted by Moore et al. (1999) showed that the low-surface-brightness galaxies in their tests were transformed to dwarf spheroidal galaxies due to tidal shocks, whereas for high-surface-brightness galaxies “the scaleheight of the discs increases substantially and no spiral features remain.” This is in marked contrast to the post-interacting galaxies observed by, e.g., Poggianti et al. (1999) and Moran et al. (2007a), which showed prominent spiral structures and well-preserved outer disks after the interaction processes that had resulted in the star-burst episodes in these galaxies.

Another proposed mechanism for producing the BO effect is the secular dynamical evolution process in galaxies, which is further enhanced by the tidal interactions in the cluster environment (Zhang 1996, 1998, 1999; Zhang & Buta 2007a, 2007b). In this scenario, tidal forces between neighboring galaxies and between a galaxy and the cluster potential serve to excite large-amplitude, open spiral, or bar patterns. Most of the morphological transformation is realized through the postinteraction mass redistribution process due to the presence of tidally enhanced density-wave patterns. In this process the radial mass accretion throughout the galaxy disk and the vertical heating of stars occur simultaneously over the time span of a few Gyr, due to the irreversible energy and angular momentum exchange between the density wave and the disk matter and the outward transport of these exchanged energy and angular momentum by the density wave to the outer disk, which lead to the gradual buildup of the bulge (Zhang 1999; Zhang & Buta 2007a, 2007b), in addition to the consumption of gas through density-wave-induced star formation. This mechanism has been shown to be able to preserve the tight scaling relation of early-type galaxies during the secular mass accretion process (Zhang 2004).

2. AN INFRARED DIAGNOSTIC APPROACH FOR THE STAR-FORMATION STATES OF CLUSTER GALAXIES

In order to assess the relevance of the different proposed mechanisms to the explanation of the BO effect, we have developed an infrared (IR) diagnostic approach that has the potential to shed new light on the BO problem using the existing and soon-to-be-available data offered by the new generation of the space IR telescopes such as *Spitzer* and *Herschel*.

Over the past three decades since the initial discovery of the BO effect, the observational studies of cluster galaxy evolution have been mostly through ground-based and space-based optical telescopes, owing to their much superior sensitivity, angular

¹ Even though the cluster velocity dispersion is generally on the order of 1000 km sec⁻¹, the velocities of galaxies at the outskirts of the clusters, especially their radial components, are generally quite low, because these outer galaxies have not been virialized and, thus, have not gained the kind of high velocity dispersion that the cluster-center galaxies have.

resolution, and area-covering efficiency. However, it is well known that optical observations suffer from dust extinction, which can shield some of the most intense star-formation activities in clusters (Geach et al. 2006). On the other hand, the existing IR observations, even those done with the state-of-the-art space IR telescopes, are limited in their angular resolution compared to optical observations. For *Spitzer Space Telescope* observations of intermediate redshift galaxies, for example, essentially only the total flux across the different IR bands are known for each cluster galaxy, with no further spatial resolution within a single galaxy. Therefore, given this state of the current IR observations, the new method is devised to make use of only the bolometric luminosity information (which is contributed most significantly by the IR bands for starburst galaxies) of cluster galaxies.

The method makes use of the fact that most of the proposed mechanisms for BO transformation will involve varying levels of dusty starburst, and furthermore these different mechanisms have different predicted characteristic IR luminosity levels, as well as different timescales for sustaining these different IR luminosity levels. Given the known BO transformation rate (which can be determined from a statistical study of the galaxy morphologies in rich clusters at the intermediate redshifts, compared to a similar study for the local universe), we can infer the roles of different proposed mechanisms by observing the different frequencies of occurrence of the varying IR-luminous galaxies in the different regions of intermediate clusters. This quantitative approach has major advantages in constraining the importance of the candidate dynamical mechanisms in transforming cluster galaxy morphologies compared to the simple-minded counting of the IR sources of a given luminosity range in an observing epoch, because the timescales of the operation of these dynamical mechanisms are vastly different, and a simple counting approach can result in serious misconceptions of the relative contributions of the different processes, as our example in the next section will show.

For a cluster region of total galaxy number N , if there are n galaxies observed to be in a luminosity range characteristic of a type of starburst event, we denote the observed frequency for that type of event f_{event} as

$$f_{\text{event}} = \frac{n}{N}. \quad (1)$$

Assume the duration of the starburst event is τ_{event} (usually believed to be on the order of 10^8 yr for strong-interaction-type events such as merger and harassment, and much longer for gas-stripping type events and for postinteraction secular evolution), after a cluster evolutionary timescale of T (on the order of a few Gyr, the exact number depending on the redshift z of a cluster), we expect a fraction

$$F = f_{\text{event}} \cdot \frac{T}{\tau_{\text{event}}} \quad (2)$$

of the cluster galaxies to have gone through morphological change due to the particular type of star-forming event alone.

The total fraction F for BO transformation between an intermediate redshift and the local universe, due to the yet-unsettled physical mechanism(s), is now fairly well determined for rich BO clusters (see, e.g., van Dokkum & Franx 2001; Franx 2004), and its value is around 20%, for example, between $z = 0.4$ and $z = 0$ (see for example Fig. 4a of van Dokkum & Franx 2001, where at $z = 0.4$ the early-type fraction is about 0.6, and at $z = 0$ the early-type fraction is about 0.8, which means a fraction of 20% of late-to-early transformation between $z = 0.4$ and $z = 0$ had happened). Since this 20% conversion fraction is for cluster as a whole, and in the later calculations we divide the cluster into three broad regions (postvirialization, active virialization, and outskirts), we estimate the morphological conversion fraction between $z = 0.4$ and $z = 0$ for the active virialization region to be 30% and for the cluster outskirts about $F = 10\%$. No estimates for the postvirialization region is given because the IR diagnostics are not available there, but it is expected that the morphological transformation process is going on at some level even in that region where the star formation has ceased.

We stress that not all of the mechanisms that can transform galaxies will include a dusty-starburst phase (for example, one proposed pathway for morphological transformation not involving a dusty starburst is dry mergers). Even for those mechanisms which can potentially invoke a dusty starburst, this phase will only be prominent when there is sufficient gas reservoir in the galaxy at the observing epoch. This approach thus predicts the maximum possible abundance of dusty starbursts that can be attributed to each mechanism, to be compared with that of the observed abundance. So for the proposed approach to work effectively, we make the implicit assumption that the BO precursor galaxies are gas-rich galaxies, which seemed to be a valid one since that was how Butcher and Oemler first discovered them (i.e., by observing their blue colors due to enhanced star formation in a gas-rich environment). For the later stage of the evolution, after the gas is consumed, we can still have the interaction and the associated morphological transformation events but no star-formation signature. However, the arguments for the validity of the fractions estimated by this approach require only that the relevant galaxies are gas rich at the observing epoch z , and that the interaction strength of the relevant mechanisms stay roughly constant throughout z . They do not require the gas fraction to remain the same throughout z . This is because we are relating the star-forming events at z with the overall morphological transformation rate F throughout z , and the latter does not require a constant gas supply. So in this sense the star-formation events at the observation epoch z is only a diagnostic signature of the underlying morphological transformation process.

We therefore cannot rule out the possibility that there are other processes that potentially could be transforming galaxies in a way that does not generate an IR-bright phase; rather we are ruling out these mechanisms as the explanation for the observed

incidence of dusty starbursts in those clusters where abundant starbursts are observed. In § 3, we will show that the starbursts that are observed in one particular intermediate redshift cluster can essentially *only* be explained via the dynamical mechanism of interaction-enhanced secular evolution, which demonstrated the power of this approach.

On the other hand, by the same principle this kind of “frequency test” can in fact be used also for sources observed in other wave bands (such as optical), as long as there is a clearly identifiable spectral or photometric feature which has a known timescale of operation.

If the timescale for the individual interaction event τ_{event} is known, we can invert the above expression to calculate the appropriate value of f_{event} for each type of interaction event in the appropriate luminosity range and for the relevant cluster region. These calculated results are tabulated in Table 1 for a hypothetical BO cluster redshift of $z \sim 0.4$. In this table we list calculated values of f_{event} for each of the proposed physical mechanisms we consider, split into several radial cluster regions, and for transforming galaxies that fall into several different classes of IR luminosity. We will describe in more detail in the following subsections of how the frequencies in Table 1 are obtained.

Note that if the predictions or observations were made at a different z (say $z = 0.2$ instead of $z = 0.4$), then the observed fraction of IR sources is expected to be lower due to the smaller amount of available gas (i.e., some of the galaxies have already completed the late-type to S0 conversion between $z = 0.2$ and $z = 0.4$). This effect is partly taken into account by the outward migration of the boundaries of the active virializing region with decreasing z , partly by the corresponding change of $F(z)$ at the new observing epoch z . Of course part of the $F(z)$ dependence accounts for the reduced elapsed time for a smaller z as well. Yet the argument should hold no matter what observation epoch one uses, as long as one concentrates to the regions where virialization is occurring. The gradually enlarging central part of the cluster then falls into the “N/A” no-prediction zone.

Note also that in Table 1 we did not break the IR luminosities of the moderately luminous galaxies at the usual luminous infrared galaxy (LIRG) level (which has the lowest luminosity value of $L_{\text{IR}} = 10^{11} L_{\odot}$), but rather at $4 \times 10^{11} L_{\odot}$. This choice of division is due to our preliminary examination of the results of Geach et al. (2006)’s *Spitzer* 24 μm observations of cluster CL 0024 + 16 at $z = 0.39$. In this cluster the majority of the IR sources detected have colors intermediate between star-forming and passive galaxies, indicating that this is possibly a transitional-type population, and these transition-type galaxies have luminosities extending to about $4 \times 10^{11} L_{\odot}$.

Furthermore, in Table 1 we have divided each cluster into three approximate zones (Goto et al. 2003a): (1) The very central postvirialization region, where the star-formation activity has ceased by the epoch of observation. For this region we do not give predictions of IR-bright sources, since we assume

these are rare due to the exhaustion of the gas for galaxies in this region. However, some postinteraction morphological transformation could still be going on here after the extinguishment of star formation. (2) The active-virialization region. For this region the virialization-triggered star-formation activity is in full swing, as will be the star-forming activities due a number of proposed mechanisms. For clusters at different redshift ranges, this intermediate zone has been found to propagate from the inner cluster toward the outer cluster region as redshift decreases. (3) The cluster outskirts. In this region the star-formation activity is elevated compared to the field, but not as vigorous as in the active-virialization region.

The predictions for the frequencies of IR-bright sources are thus given only for the latter two regions of clusters, since for the first region all of the proposed mechanisms can be made compatible potentially with the observation of a lack of star-formation activity there. The proposed observed fractions for regions (2) and (3) are further divided into subcategories for each proposed dynamical mechanism (assuming it operates alone, or is the dominating one in a particular region).

2.1. Galaxy Merger

In the popular cold dark matter (CDM) paradigm, galaxy mergers are the preferred means of morphological evolution of galaxies in clusters (see, e.g., Kauffmann 1995). Even though the likelihood of mergers in the dense regions of clusters has been questioned because of the encounter-speed arguments, the issue of to what extent mergers play a role in cluster galaxy evolution, in both the dense regions as well as in the outskirts, have never been firmly settled, especially due to the paucity of high angular resolution mid- and far-IR observations of distant clusters before the launch of the *Spitzer Space Telescope*.

For major mergers between large, gas-rich disk galaxies, we expect to see ultraluminous infrared galaxies (ULIRGs) with peak IR luminosities L_{IR} in the range of 10^{12} – $10^{13} L_{\odot}$ based on the local ULIRGs observations, though lower luminosity-ranged mergers had been observed as well, presumably between smaller galaxies or less gas-rich systems (Sanders & Mirabel 1996, Table 3). The assumptions we made to arrive at the numbers used in Table 1 for mergers are that the galaxies involved in these mergers are *large*, as well as *gas-rich* disks, a condition clearly satisfied by the BO-effect progenitor galaxies (Dressler et al. 1997). For the virializing region of a dense cluster, if we expect major mergers to be responsible for producing the observed level of BO effect, or the transformation of $F = 30\%$ of the galaxy population from spirals to S0s and other early types in the past 5 Gyr, and if we assume an interaction timescale of 5×10^7 – 1.5×10^8 yr for each of the two higher luminosity ranges listed in Table 1 (Sanders & Mirabel 1996, who further cited the merger simulations of Mihos & Hernquist 1994; also Murphy et al. 1996), equation 2 gives an observed merger fraction of $f_{\text{merger}} = 0.3$ – 0.9% for each of the higher IR luminosity ranges. We have also assumed the BIRGs (bright IR

galaxies, with L_{IR} in the range of $6 \times 10^{10} L_{\odot}$ – $4 \times 10^{11} L_{\odot}$) phase to last about twice as long as the average VBIRGs (very bright IR galaxies, with L_{IR} in the range of $4 \times 10^{11} L_{\odot}$ – $10^{12} L_{\odot}$) and ULIRGs phases; i.e., it has a timescale of 2×10^8 yr, tracing precursors and aftermaths of merger events, which leads to the estimate of $f_{\text{merger}} = 1.2\%$ in the BIRG phase.

We note that different individual merger events have different interaction kinematic configurations, which will also result in the difference in how long the merging process will last. This uncertainty in the timescales of merging events should not hamper our ability to determine the possible roles of merger in a given cluster, since the predictions of the merger scenario, both in terms of observed fractions and in terms of the luminosity of its most luminous members, are orders of magnitude different from other scenarios, and thus can tolerate this level of uncertainty. In the example we present in the next section, we will see that the predominance of moderately luminous IR sources in that cluster from many different angles precludes the possibility that merger had played a significant role in transforming the galaxy morphologies in that cluster.

For the outskirts of the cluster we assumed have a morphological transformation rate of $F = 0.1$. This leads to an average $f_{\text{merger}} = 0.2\%$ expected for the outskirts if merger is the major cause of the BO transformation, slightly higher than for the field of $f_{\text{merger}} = 0.1\%$ that is the observed value (Sanders & Mirabel 1996).

2.2. Galaxy Harassment

Because galaxy harassment is a mechanism proposed based on numerical simulations (Moore et al. 1996, 1998), rather than on observations of physical processes, the precise timescales of this mechanism are not prescribed. We expect, from the general dynamics of high-speed swing-by between galaxies, that the timescale should be on the order of 10^8 yr for each of the BIRG and VBIRG phases, similar to the less-violent phases of a major

merger. Based on this assumption, as well as the proposed *multiple* nature of the harassing encounters, which we take to be 5 for an average galaxy to complete the late-to-early-type transition through the harassment process, we arrive at an overall time scale t_{event} of 10^9 years (5 times 10^8 years in each of the two luminosity ranges), which is reasonable considering that this is essentially the timescale of the cluster-core crossing for cluster galaxies. The high-density cluster-core region is believed to be where the harassment mechanism is most effective (Moore 2004). These timescales gave the estimates of the observing frequencies quoted in Table 1.

The harassment process is expected to be much less effective away from the high-density cluster-core regions, because it depends on the strong tidal interaction between close-neighbor galaxies. We therefore set the expected observing frequency for IR-bright galaxies due to harassment in the outskirts of clusters to be nearly zero. Any observed IR-bright galaxies in those regions must be due to physical processes other than galaxy harassment. We would not expect to see ULIRGs either in the core or in the outskirts due to the action of galaxy harassment process alone.

2.3. Ram-Pressure Stripping

Like the harassment mechanism, the ram-pressure stripping mechanism is also expected to operate mostly in the dense region of a cluster, because that is where the intracluster medium (ICM) is mostly concentrated. If ram pressure is the dominant mechanism for the BO transformation, we would expect BIRGs to be preferentially located in the central virializing region of clusters, as this is a gentle process that is not expected to produce ultrabright IR sources. Furthermore, the timescale of operation of this mechanism is on the order of a cluster-core crossing time, or about 10^9 yr (Bosseli & Gavazzi 2006), though shorter timescales (down to 10^8 yr) have been proposed as well (Quilis et al. 2000; Fujita & Nagashima 1999). This leads to the frequencies of observations derived for the active-

TABLE 1

THE EXPECTED FRACTIONS AND NUMBERS OF GALAXIES TO BE OBSERVED IN EACH LUMINOSITY RANGE FOR $z \sim 0.4$ RICH CLUSTERS IN TWO DIFFERENT CLUSTER ENVIRONMENTS, FOR DIFFERENT PROPOSED PHYSICAL PROCESSES ACTING ALONE, GENERATED USING EQUATION (2).

	f_{merger}	$f_{\text{harassment}}$	$f_{\text{gas stripping}}$	$f_{\text{secular evolution}}$
postvirialization region	N/A	N/A	N/A	N/A
active virializing region	$\sim 1.2\%$ BIRGs (12)	$\sim 3\%$ BIRGs (30)	$\sim 0.6\%$ – 6% BIRGs (6–60)	$\sim 15\%$ – 30% BIRGs (150–300)
	$\sim 0.3\%$ – 0.9% VBIRGs (3–9)	$\sim 3\%$ VBIRGs (30)	$\sim 0\%$ VBIRGs (0)	$\sim 0.6\%$ VBIRGs (6)
	$\sim 0.3\%$ – 0.9% ULIRGs (3–9)	$\sim 0\%$ ULIRGs (0)	$\sim 0\%$ ULIRGs (0)	$\sim 0\%$ ULIRGs (0)
outskirts	$\sim 0.4\%$ BIRGs (4)	$\sim 0\%$ BIRGs (0)	$\sim 0\%$ BIRGs (0)	$\sim 3\%$ BIRGs (30)
	$\sim 0.1\%$ – 0.3% VBIRGs (1–3)	$\sim 0\%$ VBIRGs (0)	$\sim 0\%$ VBIRGs (0)	$\sim 0.2\%$ VBIRGs (2)
	$\sim 0.1\%$ – 0.3% ULIRGs (1–3)	$\sim 0\%$ ULIRGs (0)	$\sim 0\%$ ULIRGs (0)	$\sim 0\%$ ULIRGs (0)

NOTES—The expected number of detected galaxies for the different scenarios are given in parentheses, assuming 10 clusters, each having an average of 200 galaxies in the two outer regions (and therefore approximately 100 galaxies in each of the two regions described above). Here ULIRGs have IR luminosities in the range of $L_{\text{IR}} = 10^{12}$ – $10^{13} L_{\odot}$, (Sanders & Mirabel 1996), VBIRGs have $L_{\text{IR}} = 4 \times 10^{11}$ – $10^{12} L_{\odot}$, and BIRGs have $L_{\text{IR}} = 6 \times 10^{10}$ – $4 \times 10^{11} L_{\odot}$.

virialization region and the outskirts of a cluster due to the operation of ram-pressure stripping alone, as shown in Table 1. We would not expect to see ULIRGs in any regions of the cluster due to the ram-pressure stripping process alone.

2.4. Postinteraction Secular Evolution

The postinteraction secular evolution process refers to the enhanced star-formation and radial mass accretion process mediated by the large-amplitude open density-wave patterns such as spirals, bars, and skewed three-dimensional mass distributions (Zhang 1999; Zhang & Buta 2007a, 2007b). Secular evolution can operate in both the core as well as the outskirts of a cluster (or even in the group environment or in isolation); the only difference between these environments is the different evolution rates caused by the different strengths of the density waves, which in turn are caused by the different amount of tidal perturbation in these environments.

For the tidally enhanced secular evolution process we expect a large population of BIRGs with luminosities up to the lower range of VBIRGs. The IR manifestations of the secular evolution process depend not only on the strength of tidal perturbation, but also on the availability of gas supplies for star formation. In the postvirialization region, even though the mass accretion process may still be going on, the star-formation activity can be significantly quenched due to the paucity of gas in this region of the galaxy disk.

For the active virializing region, because the member galaxies are effectively always feeling the gentle tidal nudges of the near and far neighboring galaxies (a condition characterizing the virialization itself), we therefore set the highest timescale of secular evolution in the BIRGs phase to be 5×10^9 yr, i.e., exactly equal to the amount of elapsed time between $z = 0.4$ and $z = 0$. This of course assumes the continuous availability of gas during this time period. To take into account of the more rapid consumption of gas (i.e., a shorter star-formation timescale than the morphological-transformation timescale), we set the lower limit to be half of the maximum. Note that these timescale estimates for secular evolution assumes spiral-induced star formation and mass accretion which are a disk-specific processes. There could exist more violent primordial, clumpy mass accretion at higher z due to dynamical friction in protogalaxies, as might be what have terminated the star formation in large and early-virialized clusters such as MS0451, which we will discuss later.

For the outskirts we have assumed the star-formation timescale to be about 1.5×10^9 yr, typical of poststarburst evolution timescale (Poggianti et al. 1999) because the interaction frequency at the outskirts is expected to be low, and interaction is not continuous as in the active-virialization region.

With these assumptions we derive the expected fractions of the BIRG sources as given in Table 1. The fraction of the VBIRGs are calculated assuming an interaction timescale of 10^8 yr, describing the precursor starburst events leading to *some*

of the subsequent secular evolution. We would not expect to see ULIRGs due to the secular evolution process alone.

In this entire derivation for the frequency table (Table 1) we have implicitly assumed: (1) the constancy of the rates of the interaction processes across the redshift range under concern, (2) the availability of the gas supply to feed the star-formation activity at the epoch of the observation z , and (3) a single process dominating the BO transformation. All of these assumptions may need to be modified, at least for some clusters and during some periods of the evolution. As a result, corroborating data from other wavelengths for the clusters under study will help us arrive at a satisfactory picture of the major drivers for the morphological evolution in a given cluster, or in a population of clusters studied in a statistical sense. Apart from these implicit assumptions the only uncertainty of the Table 1 quantities comes from the timescale value τ_{event} for each proposed physical process (because F and T in equation 2 are well-determined quantities and are common for all processes in a given cluster).

3. AN EXAMPLE OF THE APPLICATION OF THE PROPOSED APPROACH

The recent $24 \mu\text{m}$ *Spitzer* observations of two distant clusters (Geach et al. 2006) have revealed elevated levels of star formation throughout the cluster up to and slightly beyond the cluster turnaround radius, both compared with that determined using optical observations and compared to values typical of the field environment at the same redshift. It also revealed very different frequencies of IR-luminous sources in these two clusters: For MS 0451–03 at $z = 0.55$, very few $24 \mu\text{m}$ sources were detected; whereas for CL 0024+16 at $z = 0.39$, a large excess of the $24 \mu\text{m}$ sources were detected (~ 150 IR galaxies over a $25' \times 25'$ area, or $9 \times 9 \text{ Mpc}^2$).

The difference in the rate of IR-luminous sources may reflect a correlation of the IR sources with the virialization state of the cluster; i.e., even though MS 0451–03 is at slightly higher z than CL 0024+16, it has larger mass and also appears to be at a more advanced stage of virialization than CL 0024+16 (Geach et al. 2006; Moran et al. 2007a), and therefore the most intense star-formation episodes may have already been over by the observation epoch (as evidenced by the presence of many passive spiral galaxies in this cluster, Moran et al. 2007a). In this case the entire cluster belongs to region 1 (postvirialization region) of the Table, which can be consistent with essentially all of the proposed mechanisms (i.e., we will not be able to discriminate among the proposed mechanisms for this particular cluster). To sum up, the lack of IR sources in MS 0451 may indicate the operations of early-epoch physical processes (such as clumpy mass accretion due to dynamical friction or spherical mass accretion) prior to the observational epoch which had effectively suppressed star formation before any other processes (such as secular evolution) would have an opportunity to generate an IR-bright starburst at the observational epoch, though the mass ac-

cretion process due to stellar density-wave structures in the passive spirals in this cluster could still continue to modify galaxy morphology without generating the corresponding starburst activity. The star-formation condition of MS 0451 is not expected to be typical for an average BO cluster at intermediate redshifts, though, since BO clusters are usually selected to contain a large population of gas-rich star-forming galaxies. We will focus our attention of the application of the proposed approach thus only on CL 0024+16.

It is well known that in disk galaxies star formation happens mostly around the spiral arms or bars, i.e., around the density-wave crest. This is because the disk is usually stable to the gravitational collapse of matter, and a density-wave shock (which is a collisionless shock induced by the nonlocal gravitational potential wave which is phase-shifted with respect to the density distribution) is needed to trigger a violent episode of star formation (Zhang 1996 and references therein). Interactions usually enhance the amplitude of the spiral density wave because the spontaneous growth rate of the density wave is usually very low (Zhang 1998), so many field spirals can have very low amplitude density waves, and remain in the disk phase even until the recent time, whereas in the cluster environment the tidal interactions remove angular momentum from the disk galaxies and also excite large seeds of nonaxisymmetric perturbations that are further amplified by the disk's intrinsic modal resonance mechanism.

Most of the $24\ \mu\text{m}$ galaxies in CL 0024+16 observed by Geach et al. (2006) show enhanced luminosity in the range of BIRGs, or $6 \times 10^{10}\ L_{\odot}$ to $4 \times 10^{11}\ L_{\odot}$, compared to their counterparts in the field ($\sim 2\text{--}3 \times 10^{10}\ L_{\odot}$ for normal disk galaxies; see Sanders & Mirabel 1996). The majority of the $24\ \mu\text{m}$ sources detected by Geach et al. (2006) display optical or NIR colors that are intermediate between starburst galaxies and passive galaxies, which indicates that this is likely a population of galaxies in the postinteraction stage, and they are going through the slow and prolonged evolution under the influence of the interaction-enhanced density waves. We now apply the frequency approach developed in the last section to further confirm the nature of these $24\ \mu\text{m}$ sources.

Geach et al. (2006) found that there are about 150 IR-luminous sources in an area of $25' \times 25'$. The majority of them are in the IR luminosity range of $6 \times 10^{10}\text{--}2 \times 10^{11}\ L_{\odot}$, which, compared with the total galaxy number of about 500 determined by Moran et al. (2005) for the same region, and taking into account of completeness estimates ($\sim 65\%$ completeness for galaxies in the range of $17.75 < I < 21.1$ and $\sim 40\%$ for galaxies in the range of $17.75 < I < 22.5$), leads to an estimation of a fraction of about 15% of IR-bright sources among the entire optical sample.² Note that Geach et al. (2006) did not carry

out the luminosity statistics of their $24\ \mu\text{m}$ sources according to the different radial ranges in the cluster, but rather estimated the luminosity statistics for the cluster as a whole. Therefore we do not have more detailed information at the present time to do a more detailed analysis in terms of the radial distributions of the frequency of the different kinds of IR-bright sources.

The derived fraction of IR-bright sources is in the correct range as predicted by Table 1 for secular evolution to account for the majority of the BO transformation between the intermediate redshift and the present for this cluster: the fraction predicted in Table 1, when averaged over the entire cluster region, would lead to a predicted BIRG fraction of around 15%. From Geach et al. (2006)'s result, it is also seen that the brighter IR sources (those in the VBIRG range of $4 \times 10^{11}\text{--}6 \times 10^{11}\ L_{\odot}$) consist of about four sources, or 0.4%, which is also consistent with the secular evolution scenario. Most significantly, there were no sources detected above the flux level of $6 \times 10^{11}\ L_{\odot}$, or no ULIRGs or strong interactions present in this cluster at this observing epoch. Improved statistics from a much larger sample would help to quantitatively assess the roles of other proposed mechanisms across the entire population of BO clusters.

Dressler et al. (1999) showed that the poststarburst galaxy fraction in their sample of 10 intermediate-redshift clusters observed using the *HST* in the MORPHS project is about 20%, similar to the fraction of IR-bright sources in CL 0024+16. Poggianti et al. (1999) confirmed that the total a + k/k + a type galaxy (the type of emission-line galaxies signifying a poststarburst population) fraction is about 20%. They had considerable trouble identifying the progenitor population of the poststarburst galaxies, however, presumably because these last only a brief period and therefore are less numerous.

In the MORPHS sample analyzed by Poggianti et al. (1999) and Dressler et al. (1999), 10% of cluster galaxies were classified as e(a) (which is a dusty-starburst spectral class), and about 40% of these (or 4% of the total) showed morphological signs of tidal interaction or were observed to be directly involved in a merger or close interaction. This is much larger than the maximum allowed fraction of mergers we estimated in Table 1 (i.e., 0.9%), which was calculated based on the observed BO transformation rate between $z = 0.4$ and the local universe. We therefore speculate that what Poggianti et al. and Dressler et al. observed could include, instead of all mergers, some interactions that were confused with mergers due to limited spatial resolution. This conclusion is also supported by the fact that in

² $3 \times 10^{10}\ L_{\odot}$, which is the typical flux level of the local dusty starburst galaxy, such as NGC 253. However, we note that not all dusty starburst at the lower IR luminosity range will lead to the conversion of a late-type to an early-type galaxy in 5 Gyr, therefore the more numerous IR sources at the lower luminosity range probably should not enter into the current statistics. This consideration is also supported by the recent result of Elbaz et al. (2007), who found higher redshift starburst galaxies to be much more IR luminous on average than the local starburst galaxies of similar morphology.

² In arriving at these fractional estimates we have considered the fact that we might need to extend the lower bound of the IR flux range from $6 \times 10^{10}\ L_{\odot}$, which is the $5\ \sigma$ detection limit of the Geach et al. observations, to closer to

both CL 0024 and MS 0451 the *Spitzer* 24 μm MIR observations by Geach et al. (2006) had revealed essentially no ULIRGs population at all.

There exists the question of whether the few highest luminosity sources (currently estimated to be in the mid range of $10^{11} L_{\odot}$ in the Geach et al. observations) in CL 0024 could have been undergoing mergers, because there is uncertainty in the conversion of 24 μm , or the rest frame 15 μm flux to the IR luminosity. We argue that this possibility could not be true for this cluster, based on the entire distribution of the IR sources in this cluster. In Table 1 the predicted rates for mergers are not only for the ULIRGs, but also for the BIRGs and VBIRGs. For a given dynamical scenario the IR source statistics in all three ranges of the IR luminosity need to be accounted for, not just those in the highest luminosity range. The overabundance of moderately IR-bright sources in this cluster is not consistent with a scenario in which merger is the dominant process for BO transformation in this cluster—if that were so a roughly 0.3%–0.9% ULIRG fraction would by itself be able to account for the $F = 30\%$ BO conversion, which leaves the rest of the 15% moderately luminous IR sources unaccounted for. Alternatively, if these moderately bright IR source also lead to transformation by some other dynamical mechanisms such as secular evolution in addition to the role played by merger, together they would be overproducing the observed 30% BO conversion ratio between $z = 0.4$ and present.

Furthermore, the observed IR sources could also not have been consistent with their being the product of either harassment or ram-pressure stripping, because these should have produced fewer IR sources based on the values given in Table 1. In addition, harassment should have erased the spiral structures, whereas most of these postinteracting galaxies were found to be spiral disk galaxies (Poggianti et al. 1999; Moran et al. 2007a). Ram-pressure stripping would also have difficulty producing the brighter portion of these IR sources in CL 0024. Therefore, a tidally enhanced secular evolution process becomes the only possible remaining candidate to account for the origin of the population of IR sources in CL 0024.

Other recent ground-based optical observations on CL 0024 using other instruments appear to corroborate our conclusions about the role of interaction-enhanced secular evolution in accounting for these excess IR sources. Moran et al. (2007b) found from the analysis of resolved optical spectroscopy of CL 0024 galaxies and a control sample of field galaxies at similar redshifts that the cluster Tully-Fisher relation exhibits higher scatter than its field counterpart. They also found that the central mass densities of the spiral galaxy population they examined were higher within the cluster virial radius than outside, with a sharp break exactly at the cluster virial radius. The cluster environment thus appears to be responsible for the creation of the increase in scatter of the Tully-Fisher relation, as well as for the increase in central density of cluster spirals within the cluster virial radius.

Moran et al. (2007b)’s tentative explanation of these observations is that the galaxy harassment process has eliminated the less-dense spirals in the cluster central regions. This explanation, however, could not account for the lack of high-central-density spirals in the cluster outskirts. So they proposed that these cluster-outskirt high-density spirals might have been eliminated by mergers. However, an obvious problem with this proposed explanation is why mergers in cluster outskirts would selectively eliminate only the high-density spirals but not the low-density spirals. Furthermore, 24 μm observations of this cluster have not revealed a significant merging population in this cluster.

The observations of Moran et al. (2007b) were also difficult to explain through any kind of ram-pressure stripping mechanisms, as these usually lead to unusual star formation gradients, whereas the enhanced scatter observed in the Tully-Fisher relation was present in both the V and the K_s band, and thus is not due to the influence of star formation or dust obscuring, but rather has to be related to the kinematic and structural changes of the cluster galaxies, as Moran et al. (2007b) concluded.

The observed trend would be most consistent with a mild level of tidal perturbation for cluster galaxies (and these perturbations are obviously more pronounced for galaxies within virializing region of the cluster, because the condition of virialization essentially guarantees a continuous interacting state of the member galaxies in the cluster virial radius), as well as the postinteraction secular evolution of the galaxy morphology and kinematics.

The secular evolution scenario could naturally produce the observed difference in the central mass density of disk galaxies inside and outside the cluster virial radius, as well as the increase in structural and kinematic scatter of these disks (Moran et al. 2007b). Note, however, that the increase of scatter is only observed for the Tully-Fisher relation of the late-type cluster galaxies within the cluster virial radius. For S0s, for example, the fundamental scaling relation in fact becomes tighter within the virial radius (Illingworth et al. 2000). This phenomenon is easily explained in the secular evolution scenario as the settling onto an “attractor” of the dynamical evolution (see § 5).

Furthermore, the fact that the blue members of a cluster show more scatter when placed on a scaling relation plot, whereas the red ones show better correlation, shows that the interactions in the cluster environment tend to disturb the perfect Tully-Fisher relation for late-type cluster galaxies compared to the field. However, as the secular evolution proceeds, the cluster environment in fact produces the tightest scaling relations at the late stages of evolution, much tighter than the counterpart of these scaling relations for the field early-type galaxies. The tidal agitation in the cluster environment is a way to disturb one dynamical equilibrium (that of late type disks) to facilitate the settling onto a new dynamical equilibrium (that of early-type morphology, which is of higher gravitational entropy).

Once again, we emphasize that the conclusions we have reached based on the analysis of CL 0024+16 serves only to illustrate the application of the approach we proposed, and the conclusion on the dominating mechanism to account for the BO effect for the majority of the intermediate-redshift clusters can only be reached once we have analyzed enough samples of rich clusters by the same approach. At the time of this writing, CL 0024 and MS 0451 are the only intermediate-redshift clusters that have been observed in this fully sampled wide-field fashion among the *Spitzer*-approved observations. A few more will be observed by *Spitzer* in Cycle 4. Numerous other observations do exist, however, for the central virialized cores of clusters and can be used to further carry out the existing program. As we have seen in this preliminary study, even the information obtained in the core region already gave plenty of hints at the underlying dynamical mechanism responsible for cluster galaxy transformation, though the addition of the cluster outskirts and group observations will help to complete the picture.

4. OTHER CORROBORATING EVIDENCE IN SUPPORT OF A SECULAR EVOLUTION ORIGIN FOR THE MORPHOLOGICAL BUTCHER-OEMLER EFFECT

4.1. Results from Sloan Digital Sky Survey

Goto (2005) analyzed the velocity dispersion of 355 galaxy clusters (with 14,548 member galaxies) from the Sloan Digital Sky Survey (SDSS), and found that bright cluster galaxies have significantly smaller velocity dispersion than faint galaxies, consistent with a picture of dynamical friction (galaxy-galaxy interaction) operating during the process of cluster virialization, which reduces the velocity dispersion of massive cluster galaxies at the expense of the increase of velocity dispersion of the less massive cluster galaxies. He also found that star-forming late-type galaxies in his sample have a larger velocity dispersion than the passive late-type galaxies (i.e., those having spiral morphology, but do not show any ongoing star-formation activity; see Goto et al. 2003b), which is once again consistent with dynamical friction reducing the velocity dispersion of the more evolved (passive) population of galaxies.

The result of Goto (2005) is consistent with our conclusion reached from CL 0024+16 that tidally enhanced secular evolution appears to be the driver for transforming the cluster galaxy morphology, since the galaxy-galaxy interaction and dynamical friction is known to excite large-amplitude density waves, which leads to subsequent radial accretion of mass and the evolution of galaxy morphological types (Zhang & Buta 2006). The Geach et al. (2006), Goto et al. (2003b), and Goto (2005) results are also mutually consistent in the sense that the 24 μ m sources that show intermediate colors between starburst and passive populations are likely to be the population in transition from starburst to passive galaxies, and these passive

galaxies, through further secular evolution, will become the earlier Hubble-type cluster galaxies observed in nearby clusters.

The role of dynamical friction during the cluster relaxation process is also reflected in the often sharp transition in galaxy properties across the cluster virial radius, or at a critical local surface density (Moran et al. 2005, 2007b; Tanaka et al. 2004; Couch et al. 2004. Figure 5 of Illingworth et al. 2000 shows another example of the change of the tightness of scaling relation for the S0 population across the cluster virial radii). These characteristics, as we commented before, can be naturally explained by the enhanced secular evolution due to the tidally induced interaction processes.

Goto (2005)'s result is on the other hand inconsistent with ram pressure's having played a significant role in causing cluster galaxy evolution. The effectiveness of the ram pressure is proportional to σv^2 (where σ is the gas density and v is the velocity dispersion), which should be more effective for galaxies with larger velocity dispersion; i.e., it should have predicted that the larger-velocity-dispersion population is the more evolved (passive) one, contrary to what is observed.

4.2. Results from the MORPHS Collaboration

The MORPHS team conducted imaging and spectroscopic studies of 10 distant clusters in the redshift range of 0.37 to 0.56. Poggianti et al. (1999) found that among the MORPHS cluster galaxies a significant overabundance of the so-called "post-starburst" galaxies with the characteristic $k + a/a + k$ spectral features, which exhibit spatial and kinematic distributions intermediate between the passive and active populations. The number density of these poststarburst populations is significantly higher in their sample clusters than in the field, so there the starburst activities prior to the $k + a/a + k$ phases were obviously triggered by the cluster environment and are the subsequent termination of the star-forming events.

One interesting thing noticed by Poggianti et al. is the mostly spiral-like disk morphology of these poststarburst galaxies from the *HST* images, showing that whatever interaction processes triggered the starburst had not changed the galaxy morphology immediately. This fact is contrary to both the merger and the harassment predictions, which require immediate change to galaxy morphologies after the interaction. The evidence for the milder tidal perturbation, on the other hand, is entirely consistent with an interaction-enhanced secular evolution scenario.

Poggianti et al. also concluded that either two timescales or two different physical processes have caused the two observed transformation processes (the halting of star formation and the spiral-to-S0 transformation). This result is supported by the later investigation of Goto et al. (2004) using the SDSS data, who found that the color evolution of the BO galaxies in their sample is much faster than the morphological evolution. In the secular evolution scenario, these two different timescales acquire a most natural explanation: the interaction events that serve to excite

the large-amplitude spiral density waves and bars may only last on the order of 0.1–1 Gyr, but the subsequent secular mass accretion process could continue for much longer, i.e., could be a significant fraction of Hubble time. Furthermore, the same process could operate on the passive phase of the galaxies involved as well, even when most of the star-formation activities have extinguished.

5. FURTHER COMMENTS ON THE DIFFERENT PROPOSED MECHANISMS FOR CLUSTER GALAXY EVOLUTION

5.1. Hierarchical Clustering and Mergers

The hierarchical clustering-CDM paradigm has been our standard paradigm for structure formation over the past few decades. However, growing evidence has pointed to the inadequacies of using this paradigm to explain the observations especially on the properties of individual galaxies.

The well-known downsizing trend of galaxy formation, not only in terms of star formation history but also in terms of mass assembly history (Cowie et al. 1996; Kodama et al. 2004; Cimatti et al. 2006 and references therein) is the most obvious contradictory evidence to the bottom-up assembly scenario that is the foundation of the CDM paradigm. While the former trend (downsizing in star formation) can perhaps be explained by proposed mechanisms such as active galactic nucleus (AGN) or star-formation feedback (see, e.g., De Lucia et al. 2006; Croton et al. 2006 and references therein), the latter trend of mass assembly downsizing (Cimatti et al. 2006) is in direct conflict with the mass assembly history predicted by the CDM paradigm. The observed early formation age of cluster early-type galaxies (Franx 2004 and references therein), even after taking into account some late formations due to the BO effect, is also contrary to the predictions of the CDM paradigm. CDM is known to significantly underpredict the extremely red objects (ERO) observed in the early universe (Daddi et al. 2000 and references therein). It also predicted significant difference in the properties of the field and cluster early-type populations (Kauffmann 1996), which is not observed. Other evidence for the difficulty of using this paradigm to explain the observed properties of galaxies can be found in Zhang (2003).

CDM predicted the late assembly of early-type galaxies, including cluster galaxies, which superficially is consistent with the morphological BO effect and with the increase in number density of early-type galaxies observed for both the cluster and field (Treu 2004 and references therein). However, unequal-mass mergers completely destroy the color-magnitude relation (Bower et al. 1998), whereas equal-mass merging among massive galaxies reduces the early-type number density, contrary to the observed early-type number density evolution. Furthermore, collisionless mergers simply cannot reproduce the high phase space density observed for the central regions of early-type galaxies (Ostriker 1980). The rotationally supported S0 disk,

which is the end product of the majority of BO transformation in clusters, is also problematic for a merger-based morphological-transformation process. These observational constraints, coupled with the high velocity dispersion of cluster galaxies, means that mergers, including dry mergers, could not have played an important role in the BO transformation, a conclusion consistent with our finding in this work based on the analysis of the properties and frequencies of the IR sources for CL 0024. The recent analysis by Elbaz et al. (2007) on the GOODS fields data also directly confirmed that a great portion of the star-formation events at $z \sim 1$ is confined within single disk galaxies, rather than due to the merging of different galaxies. The star-formation rates observed in the GOODS fields also have drastically different dependence on the densities of galaxies than that predicted by the CDM paradigm (Elbaz et al. 2007, Fig. 8). The observed density dependence of star-formation rate, however, is consistent with the expectation from the interaction-enhanced secular evolution scenario.

5.2. Infall, Stripping, Mixing, and More on the CDM Paradigm

Poggianti et al. (1999) found no evidence among the MORPHS cluster galaxies of a difference in the radial distributions of passive and emission-line spiral galaxies, though the recent result of Moran et al. (2007a) is somewhat in conflict with it. A difference of the distribution of these two populations is to be expected if significant infall had occurred. Cooper et al. (2006, 2007) described the results from the DEEP2 survey, and found that the steepening of the morphology-density relation works in the group environment just as effectively as in the cluster environment. The results from SDSS and 2dFGRS also support this conclusion. Therefore, cluster-specific mechanisms, such as ram-pressure stripping, will not be a justified cause for the group galaxy evolution. Dressler et al. (1997) concluded that the morphology-density relation indicated that more local processes are at work. Couch et al. (2004) reached similar conclusion from the 2dF survey results.

The new results of Elbaz et al. (2007) showed that at the high redshift the mechanism that relates galaxies to their environment is not simply a quencher but also a trigger of star formation: the star-formation–density relation at $z = 1$ in fact reverses the morphology-density relation trend. These authors concluded that their results are most consistent with a scenario where star formation is accelerated by the dense environment of galaxies, resulting in the faster exhaustion of their gas reservoir. This new result of the star-formation and galaxy environment dependence is inconsistent with the ram-pressure stripping picture.

As we have commented earlier, the existence of the morphology-density relation (Dressler 1980; Dressler et al. 1997) means that there could not have been a significant amount of persistent mixing of late-type galaxies from the field environment into the cluster environment during the cluster evolution process. Similar minimal-mixing conclusions have also been reached by

Abraham et al. (1996) and Morris et al. (1998). The hierarchical assembly scenario, on the other hand, advocates the gradual assembly of higher density clusters from lower density subclusters, which is slightly different from the continuous infall scenario for individual galaxies.

Through numerical simulations, Dressler (2004) and collaborators found that under the CDM paradigm there is actually significant mixing on cluster dynamical timescales, at least on the group level. This predicted mixing by the CDM, however, is in conflict with the observational evidences quoted above, including the existence of the morphology-density relation. This in fact from another side highlights the inadequacy of one of the central assumptions of the CDM paradigm (see, e.g., Peebles 1993): that of cluster formation as a purely gravitational process. This assumption is also what went into all the cluster CDM simulations that resulted in the observed mixing of the galaxy populations in the different regions of a cluster, contrary to the observational evidence of well-segregated evolution manifested in the morphology-density relation.

There is in fact very well-established observational evidence that the cluster formation process is not a purely gravitational process. Evrard (2004) reviewed many existing theoretical and observational tests of cosmology using galaxy clusters as probes and highlighted the deficiency of the cluster physics according to the CDM paradigm as “a cluster energetics problem.” Under the assumption that the principle mechanism of ICM heating is through gravitationally induced shocks, about 70% excess heat is observed beyond what is required for virial equilibrium. Furthermore, galaxy velocity dispersion in clusters shows a comparable level of excess “heat” compared to the dark matter velocity dispersion normalized to the WMAP and large-scale structure distributions. Therefore, the cluster environment is in general not in a gravitationally unstable collapsing configuration as predicted by the CDM theories. Depending on gravitational collapse alone most of the clusters as we know would not have formed. Many of the observed clusters form through their inherent hydrodynamical large-scale systematic velocities and the resultant high-speed subcluster clump mergers (such as what had happened for CL 0024, as well as for many other well-known clusters in the intermediate redshifts as studied by the MORPHS collaboration and by Couch et al. 1994), but the cause of these mergers is not gravitational collapse, but rather hydrodynamical collision due to their inherent relative velocities. A portion of the observed clusters such as MS 0451 do indeed appear to form out of gravitational collapse, however. These clusters are likely to be situated in a high-density region in the primordial mass fluctuation spectrum and, thus, are much better virialized as a whole because they satisfy better the gravitational instability condition. This latter class will appear to be more X-ray luminous for a given amount of baryonic mass. They also tend to evolve faster in terms of member galaxy morphologies as the example of MS 0451 has shown.

The excess systematic velocities of many of the protocluster clumps were thought to have originated from the so-called “primordial turbulence” at the time of cosmic microwave background (CMB) decoupling, an idea that can be traced back to the early proposals of von Weisacker (1951) and Gamow (1952), and which was subsequently substantiated by Ozernoy (1974a, 1974b, 1978). This idea has recently been shown to be relevant also to the explanation of the angular spectrum of the observed cosmic microwave background radiation (Bershadskii & Sreenivasan 2002, 2003). Peebles (1974, Fig. 1) had plotted the covariance function for the angular distribution of galaxies, and found that a power law fluctuation index n between -1 and 1 can fit the observational angular distribution of galaxies. A power-law index of $n = 0.33$ can originate from the Komogorov type of turbulence velocity spectrum, and the dissipation in turbulence can steepen the residual velocity spectrum above $1/3$, to close to the WMAP observed value of $n \approx 1$. If the primordial turbulence underlies the formation of the large-scale structure and the clusters, then the paradoxical excess heat of the ICM and excess velocity dispersion of the cluster galaxies (Evrard 2004 and references therein) would all acquire a very natural explanation, while the current CDM paradigm and the gravitational collapse picture failed to provide an explanation. In the primordial turbulence picture mergers due to inherent systematic velocities between protocluster clumps will play a much more important role, and infall and mixing which are associated with the CDM gravitational collapse will not be an important physical process during the cluster formation and evolution process.

Even though the CDM paradigm has been successful in explaining many features of the large-scale structure observations (though by no means this is the only possible way to explain it, as our above references have shown), the observations on galaxy-scaled phenomena is the area that the CDM paradigm has run into the most serious problems, both in terms of the mass profiles of galaxies along the Hubble sequence, for which it predicted the progressively later Hubble types to have a more cuspy mass density (exactly opposite to what was observed, which shows that it is the early types that possess the cuspy surface density), and also in terms of the mass assembly history, which is currently found to be anti-hierarchical (Cimatti et al. 2006). Secular evolution cannot be simply inserted into the CDM paradigm to help solve its many problems on the galaxy level, as many had hoped, because as an initial condition secular evolution assumes a physical low surface brightness (LSB) galaxy surface density profile, which is flat across the disk, not the cuspy type predicted by the CDM as a result of cold dark matter quickly sinking into the center of a galaxy.

5.3. Galaxy Harassment

Contrary to the later usage by many investigators, the early proposers of harassment intended it mainly as a mechanism for the transformation of dwarf disk galaxies to dwarf spheroidal

galaxies (Moore et al. 1996). The harassment mechanism has been shown to be ineffective during the simulations for transforming the morphologies of large disks, especially in increasing the bulge-to-disk ratio (Gnedin 1999; Moore et al. 1999). As is well known, a large fraction of the disk galaxies undergoing BO transformation are normal spiral galaxies which have large disks (Dressler et al. 1997).

Furthermore, harassment is expected to be effective only in the dense regions of clusters (i.e., virialized cores) because it depends on multiple high-speed encounters, whereas the morphology-density relation is shown to hold all the way from the dense core to cluster outskirts, and to the group environment (Dressler 1980; Dressler et al. 1997; Cooper et al. 2007).

Moreover, harassment mechanism is expected to operate by tearing apart the outer disks of a galaxy, or at least destroying the spiral structure on the disk, and yet most of the cluster post-burst populations have been found to have well-preserved disks that contain spiral structures (Poggianti et al. 1999; Couch et al. 1998; Goto et al. 2003b; Moran et al. 2007a).

We also want to emphasize that despite of some superficial similarities of the harassment mechanism and tidally enhanced secular evolution, the harassment simulations in fact produced very different remnants as a result of interaction compared to interaction-enhanced secular evolution. For example, Moore et al. (1999) states that for LSB galaxies “the bound stellar remnants closely resemble the dwarf spheroidal (dEs) that populate nearby clusters,” whereas for high surface brightness (HSB) galaxies “although very few stars are stripped, the scaleheight of the discs increases substantially and no spiral features remain.” It is clear that those dEs are not related to cluster S0s, which are the end product of BO-type evolution. Even for the HSB galaxies, however, we know from the work of Poggianti et al. (1999) and Moran et al. (2007a) that the spiral structure and thin disks survive the star-formation events induced by interactions. So these remnants cannot be the same as those from the harassment simulations, which had their spiral structure completely destroyed by the strong tidal shocks. Furthermore, since secular evolution depends precisely on the presence of density-wave features (e.g., spiral arms, bars) in the disks of galaxies to induce radial mass accretion, the operation of tidally enhanced secular evolution requires a completely different galaxy-disk physical condition (cold disk with prominent density-wave structure) than what the harassment mechanism can supply (the hot and puffed up disk devoid of density waves), despite the superficial similarities of these two proposed mechanisms.

5.4. Secular Evolution and the Origin of Galaxy Scaling Relations

In the secular evolution scenario, as a galaxy evolves along the Hubble sequence from the late to the early types, the increase in its mean surface brightness is accompanied by a corresponding decrease in the dynamical mass to light ratio

(Broeils, Haynes, & Baumgardt 1993; van der Hulst et al. 1993; Zwaan et al. 1995; Bell & de Jong 2001; Zavala et al. 2003 and references therein), these two effects compensating each other to maintain the tight scaling relations such as the Tully-Fisher and fundamental plane relations (Zhang 2004).

The empirical color-magnitude relation (CM; see, e.g., Bower et al. 1992 and references therein) has long puzzled astronomers as to its origin, especially in the face of obvious morphological transformation of galaxies as reflected in the BO effect and cluster early-type galaxy number density evolution (Franx 2004). The existence of this relation in the face of morphological transformation, however, could also naturally follow from the secular evolution process. The aging and reddening of the stellar population together with the gradual turning on of the star-forming mass reservoir (which increases the total luminosity of a galaxy) keep the galaxies on the CM relation as they redden and get more luminous. The conventional wisdom had always been that the constant slope of CM relations across redshift z means that this is not an age-mass relation, but rather a metallicity-luminosity relation (Ellis et al. 1997; Kodama et al. 1998), and the fact that most intermediate and nearby cluster early-type galaxies fall on tight color-magnitude relation means that their stars formed at high redshift (Franx 2004). This, however, implicitly assumed that the total luminosity L of a galaxy does not increase with time. The density-wave-induced secular evolution process results in a continued ignition of more and more baryonic star-forming material, as well as a in a continuous radial inflow of baryons to increase the effective mass of the early-type galaxies, so that when this process is considered the total luminosity L of a galaxy can increase with time. Although with the aging and reddening of the stellar population, the M/L ratio of the early-type galaxy increases (i.e., the average stellar population dims with age), the total L can nonetheless increase because the increase of M due to secular evolution is much more substantial.

By observation, it was found that many elliptical galaxies contain substantial outer disks (Franx 2004 and references therein). The L^* disk ellipticals are found to form a continuous sequence with the S0s. Thus the continuous secular evolution through disk-related mass accretion process can conceivably lead to the increase of the elliptical galaxies’ mass throughout the Hubble sequence. For the cluster early-type population, it was found by Fasano et al. (2000) that the S0 population is correspondingly reduced for clusters with a large elliptical population, and vice versa. This gives indirect support to the idea that the secular evolution process can in fact carry an early-type galaxy across the S0 Hubble type into disk ellipticals.

So far, high- z surveys have not uncovered many red cluster galaxy progenitors, presumably this means they are yet to be transformed into such. The presumed high- z progenitors of the nearby early-type galaxies, the Lyman break galaxies (Steidel et al. 1996), were found to be much less massive than the average early-type galaxies in the nearby universe (Papovich

et al. 2001; Shapley et al. 2001). It is likely that the mass of these high- z early-type galaxies have grown significantly since these earlier epochs through the secular mass accretion process. This explanation is one way to account for the “progenitor bias” as well as the increase in number density of early-type galaxies with decreasing redshift (Treu 2004 and references therein).

The explanation of the nature of the color-magnitude relation as effectively an age-mass relation resolves the dilemma faced by the conventional explanation, that while on the one hand the observed morphological and spectroscopic BO effect for cluster galaxies means that not all cluster galaxy stars are old, on the other hand the CM relation in the nearby universe is so tight that it would have implied a uniform high formation redshift of the major population of stars in these early-type cluster galaxies by the conventional wisdom. This explanation also naturally accounts for the fact that for every cluster observed (even those in the nearby universe), there are always some blue outliers that were off the main track of the cluster CM relation. This shows that galaxies only settle onto the CM relation as they age, since when starting off they are generally not already on the CM relation. The CM relation is thus another “attractor” of the secular evolution process.

This new explanation of the meaning of color-magnitude relation is also consistent with the recently established downsizing trend (see, e.g., Cimatti et al. 2006; Kodama et al. 2004 and references therein) for structure formation and mass assembly, which require the oldest object to be the most massive ones; this, coupled with the empirical CM relation, means that the red objects are indeed older, in addition to being metal rich. The most recent observations have by now given direct confirmation that the colors of the early-type galaxies in the local universe are indeed correlated with the mean age of the stellar population (Barr et al. 2007).

6. CONCLUSIONS

In this paper we have reviewed the existing dynamical mechanisms to account for the origin of the cluster galaxy morphological transformation, and pointed out serious contradictions to observed properties of cluster galaxies when many of these mechanisms are examined in detail. We have proposed a new approach of using panoramic space infrared observations to quantitatively assess the roles of the different proposed mechan-

isms in transforming the cluster galaxy morphology and in producing the Butcher-Oemler effect. The preliminary application of this approach, coupled with a wealth of published results analyzed under new light, points to interaction-enhanced secular evolution process as the most likely contributing mechanism for producing the morphological Butcher-Oemler effect. This conclusion is supported, most importantly, by the following observational evidence: that the interaction-induced morphological-transformation process in clusters appears to be a disk-related process with well-preserved density-wave patterns present on the galaxy disk through most of the evolution process; that the transformation appears to go through a universal sequence of starburst, poststarburst, passive spiral, S0, and disk elliptical stages; that the quenching of star formation appears to happen on a shorter timescale than the corresponding morphological-transformation timescale; that the mid-infrared signature of the interacting events shows the predominance of a large population of moderately infrared-bright galaxies, which have optical and near-infrared colors as well as number densities consistent with their being the population in the transitional stage between starburst and passive galaxies. All of the above evidence is consistent with the interaction-enhanced secular evolution scenario for galaxy morphological transformation in clusters.

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